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A COMPUTER SIMULATION OF SKYLAB DYNAMICS AND ATTITUDE CONTROL FOR PERFORMANCE VERIFICATION AND OPERATIONAL SUPPORT

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16. ABSTRACT

A simulation of the Skylab attitude and pointing control system (APCS) is outlined and discussed. Implementation is via a large hybrid computer and includes those factors affecting system momentum management, propellant consumption, and overall vehicle performance. The important features of the flight system are discussed; the mathematical models necessary for this treatment are outlined; and the decisions involved in implementation are discussed. A brief summary of the goals and capabilities of this tool is also included.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TECHNICAL MEMORANDUM X-64876

A COMPUTER SIMULATION OF SKYLAB DYNAMICS AND ATTITUDE CONTROL FOR PERFORMANCE VERIFICATION AND OPERATIONAL SUPPORT

INTRODUCTION

During the final design and verification phases of the Skylab Program, it became apparent that many questions regarding the performance of the attitude and pointing control system (APCS) could be answered only by detailed simulation. This was particularly true in the areas of momentum management and propellant consumption where performance was strongly affected by events that occurred previous to the period in question. This led to the development of a hybrid computer simulation for evaluating the propellant requirements for certain planned and proposed activities. It was also recognized that such a simulation tool might be required to answer questions about system performance that would arise during the 8-month life of the vehicle. The salient features of this simulation tool are described in this document.

SKYLAB ATTITUDE CONTROL SYSTEM

Requirements

The Skylab space station was designed to serve as a stable, manned platform for solar, stellar and earth observations. Prelaunch mission plans called for a total mission length of 8 months with three 3-man crews visiting the laboratory for periods up to 56 days. Because the mission was of such duration and because the vehicle would be manned during much of its life, an efficient, reliable attitude control system was called for. Experiment requirements also called for a design capable of very accurate pointing. For example, the primary experiment mode, solar pointing, called for a pointing stability of 2.5 $\widehat{\text{sec}}$/15 min. These requirements dictated a body pointing system capable of maneuvering and pointing the entire vehicle with a stability of about 10 $\widehat{\text{min}}$/15 min and an experiment pointing control system capable of providing the remainder. This requirement for body pointing resulted in a momentum storage system for primary attitude control. The desire to minimize the contamination of the experiment optical surfaces forced the adoption of a cold gas reaction jet system. Because of the fairly limited impulse storage capability of such a system, it was necessary to utilize gravity gradient torques on the vehicle to dissipate momentum accumulating in the momentum storage system.

The resulting total control system was efficient in terms of consumables and was capable of great flexibility. However, the system was difficult to analyze because its performance in any given situation was greatly influenced by events which had occurred previously. For example, a particular maneuver which might be accomplished very easily if performed alone could be significantly difficult if performed in conjunction with other maneuvers or experiments. This problem usually manifested itself in large propellant expenditures and, in some cases, temporary loss of high accuracy attitude control. The former affected the number of maneuvers that could be performed with the fixed propellant supply; the latter degraded data taken during the experiment.

Description

Figure 1 shows the major portions of the Skylab space station as it appeared on orbit with an Apollo ferry ship docked at the end port. The Apollo Telescope Mount (ATM) contained the solar telescopes, as well as most of the attitude control system equipment. The workshop contained the crew quarters and work stations. The multiple docking adapter contained the crew's attitude control panel. The reaction jet modules were located on the after most portion of the workshop.

Torques for control of the Skylab vehicle's attitude were provided by three double gimbal control moment gyros (CMGs) and by six cold gas thrusters utilizing high pressure nitrogen. The thruster attitude control system (TACS) was designed to back up and agument the CMG system, which was the primary control actuator system. Attitude and rate information was supplied by a system of rate gyros, sun sensors, and a star tracker. Commands to the various actuators were issued by an onboard digital computer. The primary Skylab attitude was solar inertial (i.e., the vehicle Z-axis was pointed to the sun) and was necessary for solar observations and electrical power generation. From time to time the vehicle was also placed in an attitude for earth observations. In this case the vehicle was maneuvered so that the Z-axis was aligned with a radius vector from the center of the earth to the spacecraft. An attitude hold mode was also incorporated which allowed the vehicle to be maneuvered to any desired inertial attitude which the system would then hold. All maneuvers were performed as eigenaxis rotations.

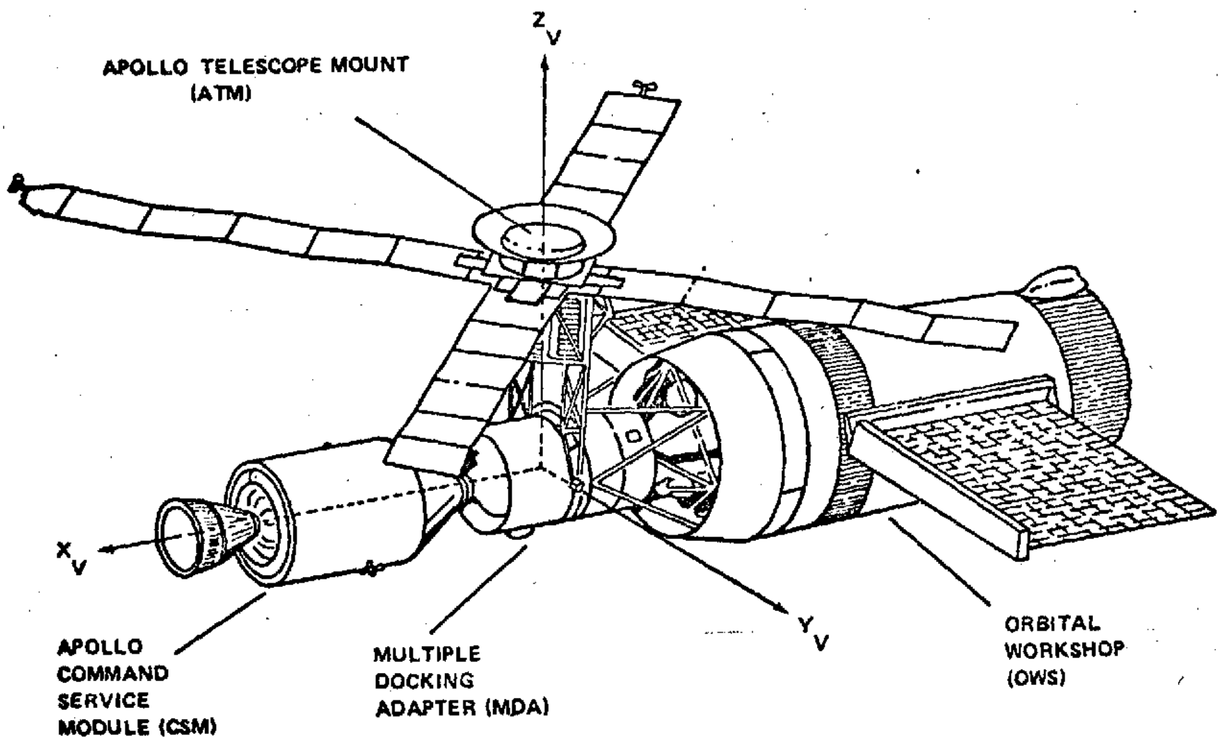

Figure 1. Skylab orbital assembly.

The CMG system stored angular momentum resulting from the various distrubance torques acting on the spacecraft. Since some portions of these are noncyclic, momentum would tend to accumulate in the CMG system until it was saturated and lost the capacity to control the vehicle. To prevent this from occurring, two desaturation procedures were used. One of these utilized the thruster system to reduce momentum by adding the proper angular impulse. The second technique maneuvered the spacecraft so that the gravity gradient torque reduced the momentum to the desired level. This procedure utilized no consumables but required the use of approximatly one-third of each orbit for gravity gradient (gg) momentum dumping. Effectively the gg dump scheme was the primary mode and the mass expulsion technique was only used when circumstances made it impossible to hold the CMG momentum below the saturation level. After system initialization (CMG spin up, etc.), control for all maneuvers and attitude hold situations was to be provided by the CMGs with desatuation firings from the TACS as required. There was, however, provision for reverting to the TACS system in case of difficulty with the CMG system. When operating on the thruster system only, a minimum impulse bit/deadband scheme was used. This mode could be activated by command, if desired, or automatically if the onboard computer judged the system to be responding abnormally. All of the

TACS propellant was stored in spherical tanks at the rear of the spacecraft. These were designed to hold 271 340 N-sec (61 000 lb-sec) of usable impulse and no provision was made for replenishment. By way of comparison, this translates into only 4 to 5 days of control in the "TACS only mode." This gives an indication of the degree of dependency on the CMG system for control and illustrates why the propellant supply had to be utilized effectively.

SCOPE OF SIMULATION

The Skylab control system simulation was designed to evaluate performance during typical mission operations and to supply mission planners with propellant consumption figures. These figures were used to establish propellant allocations for the various experiments, which in turn fixed the number of experiment operations which could be planned. Because of these goals and the influence of previous events on system performance, a simulation operating much faster than real time was essential. Fortunately, many of the finer details which could have been included were found to have little or no influence on system behavior over the periods of time of interest. This allowed a time scale of 100 to 1 in some restricted cases and 50 to 1 in most cases. This meant a 24-hour (16-orbit) flight plan could be simulated in about 30 min of actual time. The simulation had to include gravity gradient and venting torques as well as provisions for aerodynamic torque calculations.

An accurate model of the gravity gradient momentum dump scheme was a necessity as was a dependable model of all aspects of the CMG steering law. All interfaces between the CMG control scheme and TACS had to be modeled because interplay between these systems was to be a major simulation feature. In addition to all these aspects, the simulation had to have the capability of being flown through a series of maneuvers with a minimum of setup time. The ability to fail a major component, such as a CMG or TACS engine, and to evaluate performance also had to be included. Provision for altering vehicle inertias on command while leaving control system gains fixed was included so that behavior during docking and undocking could be studied. This also provided the capability to evaluate the sensitivity of the momentum management scheme to uncertainties in the vehicle inertia properties. Probably as important as any one aspect was the capability of outputing results in a variety of fashions. Results were recorded graphically via strip chart recorders in most cases and this provided a very quick comparison and evaluation of behavior. Quantities which required higher resolution were read out digitally. In some special cases X-Y recorders were used to plot one variable against another. A three-dimensional cathode ray tube display was also available for use in evaluating CMG momentum vectors in three dimensions.

OVERVIEW OF BASIC MATH MODEL

The Skylab hybrid simulation basically consisted of a mathematical model of the rotational dynamics of a rigid body in earth orbit with CMG/TACS control and all important associated distrubance torques. Flexible body dynamics capability was included with models of up to six bending modes. However, the flexible body effects were neglible and were not generally incorporated. Disturbance torques caused by aerodynamics, gravity gradient, venting, and TACS thrust impingement were included. The most important of these was gravity gradient. Venting, however, was quite important when large torques or long time periods were involved. Aerodynamic torques were essentially negligible compared to the gravity gradient, and the thrust impingement torques were overshadowed by the actual thruster torques.

Orbital dynamics were not included since a kinematic model was found to be sufficient. Ellipitical orbit capability was included but was not needed since the actual orbit was very close to circular. Motion of the orbit plane was not included in the model since the rate of change of the associated variables is slow enough to be considered constant for a given day.

Coordinate Systems

The coordinate systems used in the simulation were defined in the same manner as those used in the Appollo Telescope Mount Digital Computer (ATMDC) flight program. The inertial reference frame for the simulation was the orbital reference which is defined with the X-axis in the orbit plane and normal to the sunline with positive direction toward the evening terminator. The Y-axis is normal to the orbit plane and positive north (Fig. 2). The solar reference is then defined by rotating about the X_0-axis through an angle η_X. The solar inertial reference is defined by performing an additional rotation about Z_S through an angle γ_Z. The body frame is defined in Figure 1 and is related to the solar inertial reference by a general three-axis rotation. Principal axes of inertia are related to the body axis by a constant matrix of direction cosines.

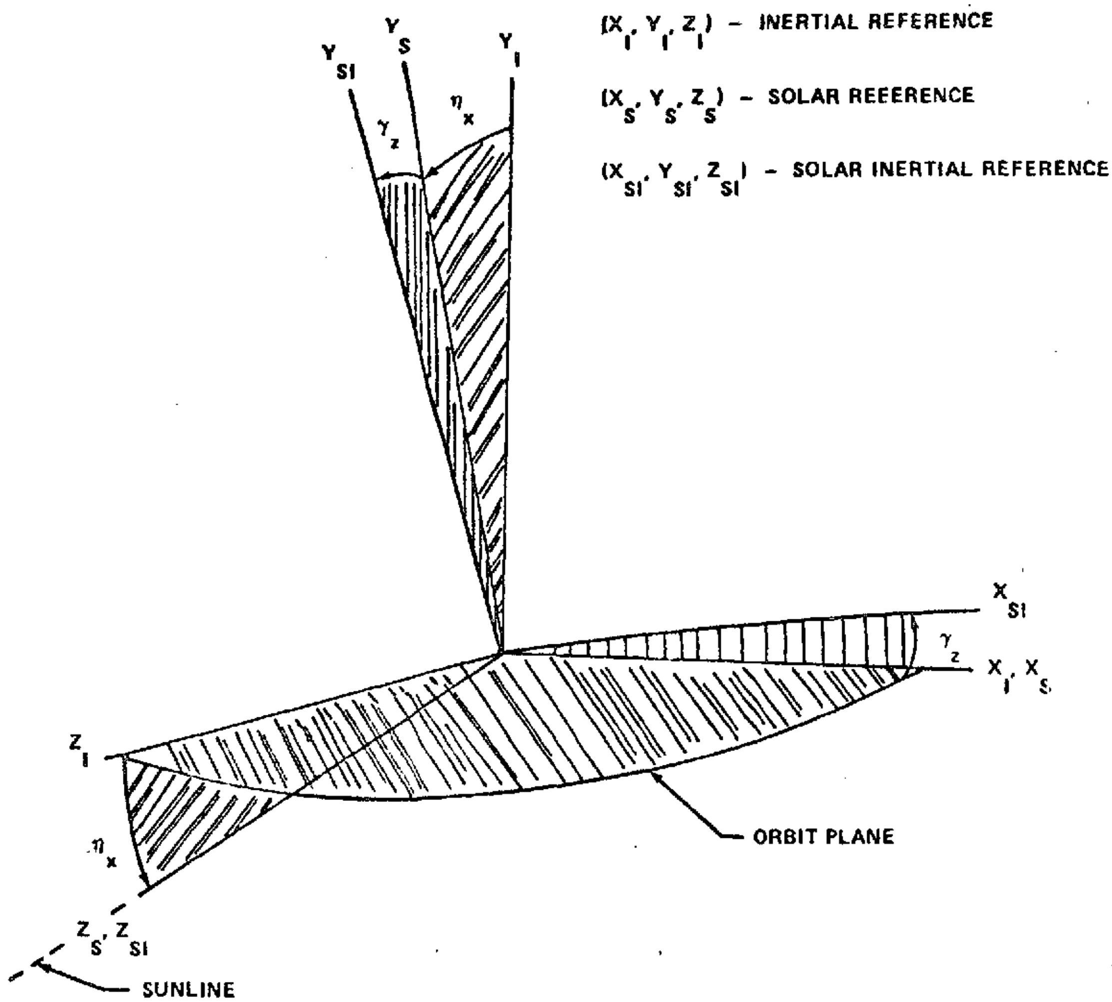

Figure 2. Coordinate system used in the simulation.

CMG/Vehicle Dynamics

The equations of motion of the system are easily derived from Newtonian mechanics and are represented by

$$I \dot{\vec{\omega}}_V + \vec{\omega}_V \times (I \cdot \vec{\omega}_V + \vec{H}_{CMG}) + \dot{\vec{H}}_{CMG} = \vec{T}_{TACS} + \vec{T}_{DIST} \quad , \quad (1)$$

where I is the moment of inertia dyadic, $\vec{\omega}_V$ is the vehicle angular velocity, $\dot{\vec{H}}_{CMG}$ is the CMG momentum, $\vec{T}_{TACS}$ is the thruster torque, and $\vec{T}_{DIST}$ is the summation of all disturbance torques. $\dot{\vec{H}}$ is the time rate of change of the total CMG momentum expressed in the body reference frame, and it is directly relatable to CMG gimbal angle rates through the geometry of the individual CMGs and their mounting configuration (Fig. 3). This quantity may be thought of as the control torque since its desired value is computed from a combination of vehicle attitude and rate errors with appropriate gains. In the simulation, attitude and rate sensors were modeled ideally. A model allowing a specified rate of gyro drift was constructed after launch and was used in some parameter studies before the six-pack was installed. Under normal operating circumstances, the CMG torque command is calculated in the following manner:

$$\dot{\vec{H}}_c = a_0 \phi + a_1 \omega_V \tag{2}$$

where ϕ is a 3×1 column matrix of the attitude errors, a_0 is an attitude gain matrix, and a_1 is a rate gain matrix.

The function of the CMG steering law is to transform the command torque $\dot{\vec{H}}_c$ into gimbal rate commands. This portion of the system is quite involved and cannot be stated in detail in a compact form. This portion of the simulation was constructed with equations and logic identical to those used in the flight computer. A detailed representation of this can be found in References 1 and 2. For purposes of this document let it suffice to state

$$\dot{\vec{\delta}}_c = f\left(\dot{\vec{H}}_c, \vec{\delta}\right) \quad . \tag{3}$$

Having generated the commanded CMG gimbal rates, the next step is to determine the actual gimbal rates via the individual CMG models. The CMG torquer dynamics was modeled with a first order lag network. Since software stops were encountered prior to the actual hardware stops on the flight, the gimbal stops were modeled simply as limits on the gimbal angles. Having produced the actual gimbal rate, the gimbal angle is produced by

$$\vec{\delta} = \int \dot{\vec{\delta}}\, dt + \vec{\delta}_0 \quad . \tag{4}$$

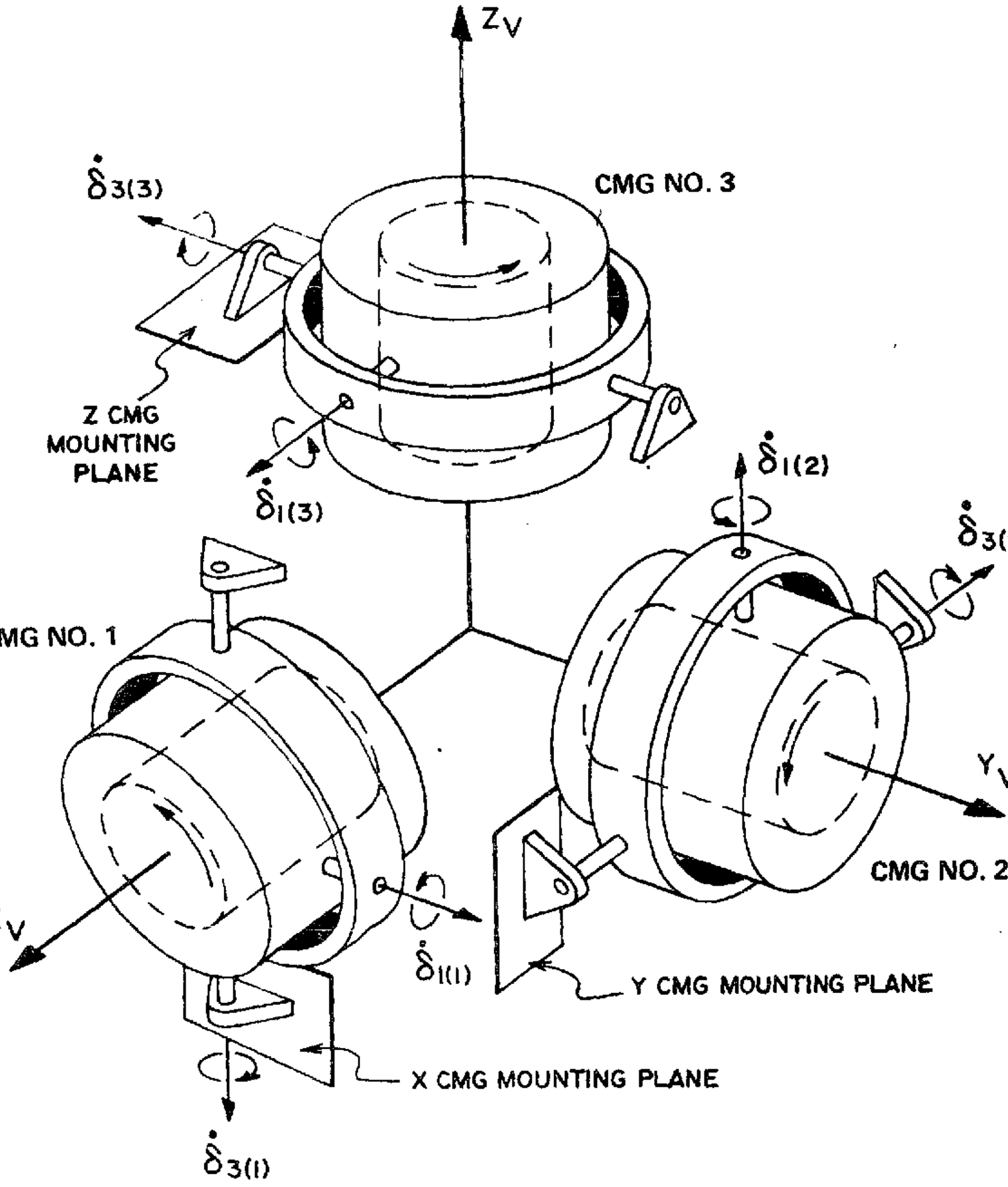

Figure 3. Typical mounting configuration of the CMGs.

Having determined both the gimbal rates and gimbal angles, the momentum effects are calculated for each CMG and the total is found by vector summation. The relationship between $\vec{H}$ and $\vec{\delta}$ is easily derived from the geometry for each CMG (Fig. 3). The relationship between $\dot{\vec{H}}$ and $\dot{\vec{\delta}}$ can be found by taking a derivative.

Assuming that the disturbance torques are known, equation (1) can be solved for the angular acceleration $\dot{\vec{\omega}}$. Then

$$\vec{\omega}_v = \dot{\vec{\omega}}_v \, dt + \vec{\omega}_{v0} \quad . \tag{5}$$

Next, the time derivatives of the quaternions are calculated:

$$\dot{\vec{q}} = - 1/2 \; \tilde{\Omega} \; \vec{q} \tag{6}$$

where $\tilde{\Omega}$ is a 4×4 skew-symmetric matrix of the components of $\vec{\omega}$. Then,

$$\vec{q} = \int \dot{\vec{q}} \, dt + \vec{q}_0 \quad . \tag{7}$$

This essentially completes the description of the CMG/vehicle dynamics. Direction cosines and/or Euler angles can be found from the quaternions. In the interest of brevity, detailed descriptions of particular reference frames and transformations used for maneuvers will not be given here. In general, direct quaternion multiplication was employed, and direction cosines or Euler angles were not used except where necessary to provide the proper interface with flight operations. Logic and equations governing momentum desaturation maneuvers were exactly the same as those used in the flight program. Also, logic for the desaturation thruster firings, CMG special reset routine, CMG cage routines, etc., were identical to the flight program to whatever degree possible. Different sample rates between flight and simulation were unavoidable for all practical purposes. Description of all logic and equations in the flight program can be found in Reference 2.

Disturbance Torques

The most important of all disturbance torques was the gravity gradient. This torque can be accurately modeled with accurate mass data by

$$\vec{T} = 3 \, \Omega_0^2 \; \hat{r}_0 \times I \cdot \hat{r}_0 \tag{8}$$

where Ω_0 is orbital rate, $\hat{r}_0$ is the unity orbit radius vector resolved in the body frame, and I is the moment of inertia dyadic.

The aerodynamic torque model was three dimensional and considered a density which varied with orbital position and altitudes as well as the effect of attitude on the various aerodynamic moment coefficients. Thruster impingement torques were modeled simply as an additional constant torque associated with each engine firing. Capability to model a vent torque of arbitrary profile was included and extended so that a number of scheduled vents could be linked in series. It was found, however, that a constant torque of equivalent angular impulse was equally as good for most purposes.

SIMULATION PHILOSOPHY

In order to implement the various mathematical models so that the joint criteria of accurate results and high run speed were met, a number of problems had to be solved or acceptable compromises found. In particular, it was mandatory that the simulation yield an accurate history of TACS thruster firings and propellant consumption. A necessary condition in meeting this requirement was to accurately simulate the CMG momentum accumulation and the gimbal angle responses. Furthermore, it was necessary to have the simulation perform this task at run speeds as fast as 100 times real time.

It was found that the requirement on the CMG and TACS dynamic responses were generally in direct conflict with the run speed requirement. The attitude and angular rate transient responses are particularly affected by high run speeds. Unrealistic overshoot in the simulated attitude response causes the CMG steering law to over-react resulting in possible gimbal stop encounters, momentum saturation, and invalid TACS firings. This occurs because the simulation (as indeed the Skylab vehicle attitude control system) constitutes a sampled data control system. This problem is avoided if

$$N(\Delta t)_{SIM} \leq (\Delta t)_{VEH} \quad , \qquad (9)$$

where N represents the simulation run speed (50 fast, etc.), $(t)_{SIM}$ is the time required for the simulation digital computer to cycle through its calculations, and $(t)_{VEH}$ is the ATMDC computation interval. Indeed if the relation (g) were an equality, this would be the ideal case as far as simulating the Skylab dynamics.

Another problem encountered was drift of the analog components. This effect primarily impacts the long term behavior of the CMG momentum, and can obscure the true momentum accumulation caused by disturbances and attitude maneuvers if compensation is not provided.

To meet the performance criteria enumerated in the previous discussion, two primary courses of action were followed. The first involved choosing the best implementation for each model, i.e., digital or analog. Having performed this task, compensation was provided, where necessary, to ensure that the simulation provided realistic results. A brief discussion of methodology employed follows.

Implementation Methodology

There are several schools of thought regarding the division of a hybrid simulation between the digital and analog computers. No general discussion of the merits of each will be given. The aim here is to present the guidelines used with the Skylab TACS simulation. It is felt that this is a workable and practical methodology.

The criteria used follows:

Criteria for Digital Implementation of a Model

D1. Models that are inherently digital in nature.

D2. Low frequency models if the higher accuracy of the digital is required.

D3. Models requiring the storage of large quantities of data.

D4. Models whose characteristics or constants are varied or changed frequently.

Criteria for Analog Implementation of a Model

A1. Models with high frequency dynamics.

A2. Models that require excessive time for the calculations if implemented digitally.

A3. Any model that satisfies the criteria for implementation on either the digital or the analog.

The basis of the final criterion for analog implementation (A3) is that the digital computation time should be kept as small as possible. The following is a list of the major elements of the simulation, how simulated, and the criteria applicable.

	Element or Model	Implemented On	Reasons
1.	Onboard Digital Computer Attitude Control Equations	Digital	D1
2.	Vent Torque Model	Digital	D3, D4
3.	Gravity Gradient Torque	Digital	D2
4.	Aerodynamic Torque	Digital	D3, D4
5.	TACS Dynamics	Analog	A1, A2
6.	CMG Dynamics	Analog	A1, A2
7.	Rigid Body Dynamics	Analog	A3
8.	Flexible Body Dynamics	Analog	A1

The final configuration is shown in block diagram representation in Figure 4.

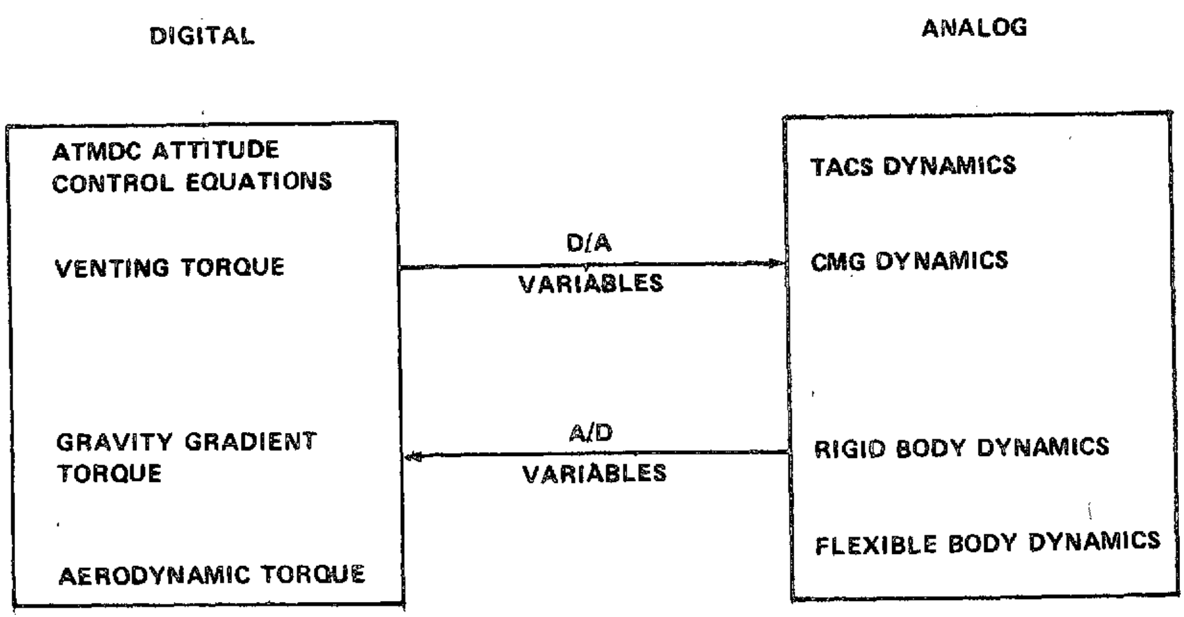

Figure 4. Utilization of EAI-8900 in Skylab hybrid TACS simulation.

Compensation

The resulting digital program required approximately 0.025 sec for the completion of all calculations. Referring to relation (9), the equivalent computation time at 10 fast is 0.25 sec. Since the onboard cycle time for the CMG control system was 0.2 sec, the 10 fast run speed was considered the standard for simulation checkout.

To obtain matching responses for the CMG control system at other run speeds (1, 50, 100 fast), compensation of the control loop was required. The approach taken was to modify the CMG feedback control gains for attitude error and attitude rate. A compensation factor calculated using the following algorithm yielded good results:

$$K_c = \frac{1 - A\left(1 - \frac{N}{10}\right)}{1 + B\left(1 - \frac{N}{10}\right)} \tag{10}$$

where A and B are constants determined experimentally and N is the run speed. The attitude gain (K_0) and rate gain (K_1) were then modified as follows:

$$K_0 = K_0/K_c$$

$$K_1 = K_1 \cdot K_c \quad . \tag{11}$$

Since rigid body and CMG dynamics were implemented on the analog, it was necessary to provide some compensation for momentum drift. The technique employed consisted of digitally calculating an ideal system momentum in the vehicle reference frame:

$$\vec{H}_I = \int (\vec{T}_D - \vec{\omega}_V \times \vec{H}_I)\ dt \tag{12}$$

where $\vec{T}_D$ is the external disturbance torque and ω_V is vehicle angular rate. An error momentum is determined by differencing $\vec{H}_I$ and the system momentum

$$\vec{H}_E = \vec{H}_I - \vec{I}\omega_v - \vec{H}_{CMG} \tag{13}$$

where $\vec{H}_{CMG}$ is CMG momentum and I is the vehicle inertia tensor. A corrective torque is then calculated and is applied to the vehicle dynamics:

$$T_C = K_B \vec{H}_E \quad . \tag{14}$$

The parameter K_B specifies the frequency below which the digital integration of torques is dominant over the analog integration. Therefore, a proper choice for K_B is one that will allow the analog to function as the dominant integrator at medium and high frequencies and allow the digital to provide protection only against long term drift. It also is important that K_B be chosen small enough that a simple rectangular integration scheme can be used in equation (12). Otherwise, nothing has been gained by implementing the rigid body dynamics on the analog rather than digital. Therefore, a restriction for K_B is defined by:

$$K_B << 1/N(\Delta t)_{SIM} \quad . \tag{15}$$

For the Skylab simulation, it was found that a K_B of 0.02 was sufficient to provide the drift protection capability.

The final result of this effort was a simulation which met both the requirements for accuracy and high run speed. For example, all features with the exception of flexible body effects could be simulated accurately at speeds up to 50 times real time. Flexible body dynamics required run speeds no greater than about 10 fast. Some maneuvers or situations which did not require large numbers of TACS engine firings could be simulated accurately at speeds up to 100 fast.

SUMMARY

This report has briefly described the major steps involved in developing and implementing a comprehensive simulation of vehicle dynamics and control system interaction. Basically these steps were: (a) analyzing the systems to be treated and the answers being sought to determine what features should be included, (b) developing the mathematical models involved with these features, and (c) implementing these in a manner that best satisfies the operational goals set in (a). The proof of any simulation development such as this lies with the results obtained. In this regard the reader is referred to a companion report now being prepared for publication* which deals exclusively with results obtained from this simulation and compares those results with the behavior of the real system. Generally this comparison was very favorable and the simulation was used routinely to predict future system behavior during the next 24 hour period. It is hoped that information in these two documents will be of use to engineers faced with the development of simulation tools for similar purposes in the future.

*McNiel, D. and Hammer, M.: Skylab Mission Planning Support Through the Use of Hybrid Simulation. To be published as a NASA TMX at MSFC.

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APPROVAL

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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